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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

CIRCULATION CONTROL – AN UPDATED BIBLIOGRAPHY OF DTNSRDC RESEARCH AND SELECTED OUTSIDE REFERENCES

by

Robert J. Englar, Michael B. Stone, and Marion Hall

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AVIATION AND SURFACE EFFECTS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

September 1977 Report 77-0076

CIRCULATION CONTROL – AN UPDATED BIBLIOGRAPHY OF DTNSRDC RESEARCH AND SELECTED OUTSIDE REFERENCES

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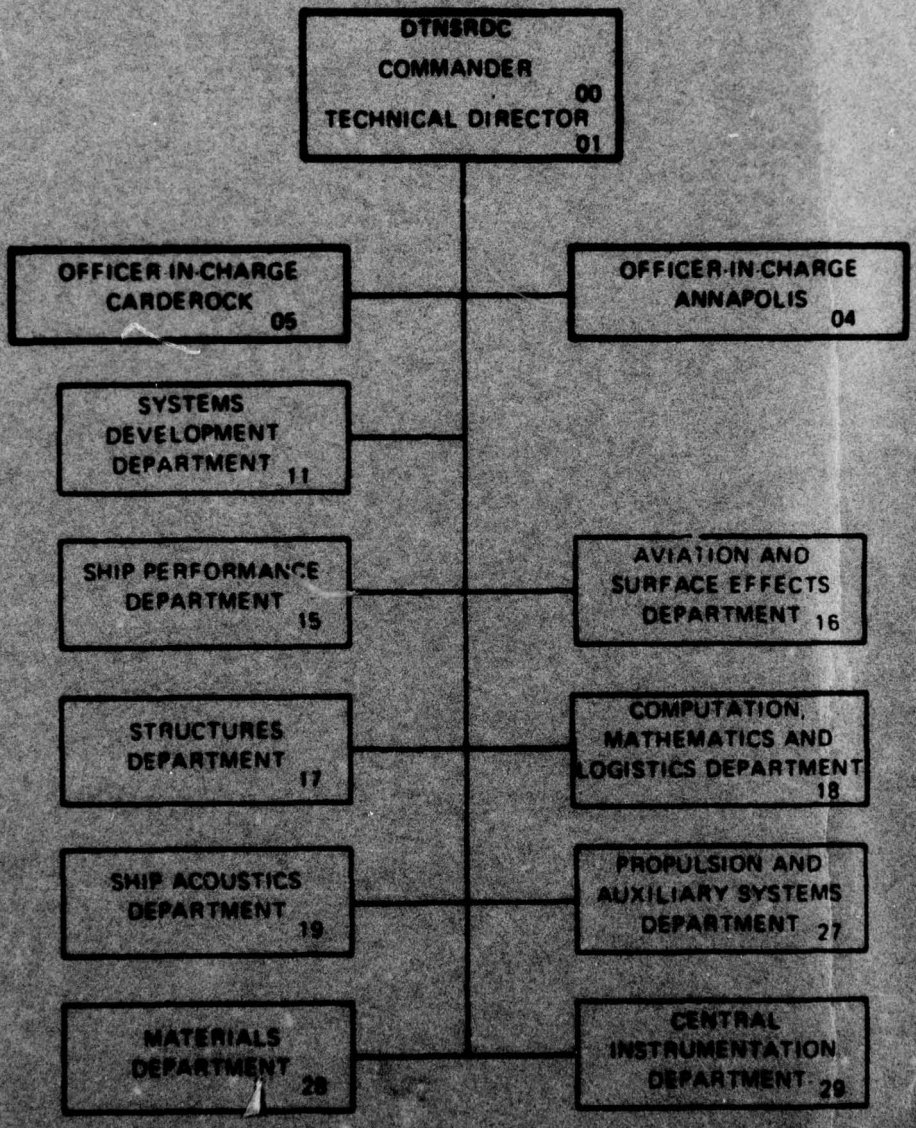

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This report is an update of a previously published bibliography of technical notes, formal reports, and technical papers by personnel of the Aviation and Surface Effects Department, David W. Taylor Naval Ship Research and Development Center (DTNSRDC). The update covers publication in the time period from the beginning of 1969 through mid-1977.

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Tangential Blowing	V/STOL Aircraft

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The citations are arranged chronologically and represent the technology of circulation control as it has developed at DTNSRDC. This report also contains appendices of selected outside references which are pertinent to circulation control.

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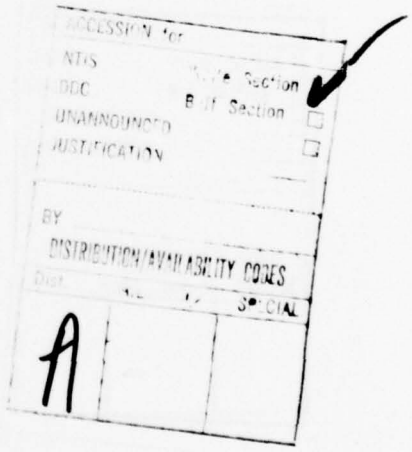

ABSTRACT

This report is an update of a previously published bibliography[1] of technical notes, formal reports, and technical papers by personnel of the Aviation and Surface Effects Department, David W. Taylor Naval Ship Research and Development Center (DTNSRDC). The update covers publication in the time period from the beginning of 1969 through mid-1977.

The citations are arranged chronologically and represent the technology of circulation control as it has developed at DTNSRDC. This report also contains appendices of selected outside references which are pertinent to circulation control.

ADMINISTRATIVE INFORMATION

The work represented by the studies reported herein was supported by the following sponsors: Naval Air Systems Command, Office of Naval Research, National Aeronautics and Space Administration, Naval Material Command, and in-house IR/IED programs of the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). This bibliography is published under funding from Project F41.421.210, Work Unit 1-1619-200.

INTRODUCTION

The technology of circulation control has evolved steadily at DTNSRDC during the last 8 1/2 years, and many requests for information have been received from others working in the field. The concept involves the ejection of a thin jet of air (or fluid) over the rounded trailing edge of an otherwise conventional airfoil (hydrofoil). The jet sheet adheres to the trailing edge, moves the stagnation points to the lower surface and thus controls the circulation and lift on the foil. This very powerful method of force generation essentially independent of the foil's inclination to the fluid stream has found a great many useful applications in the fields of aero- and hydrodynamics. This compilation is an attempt to document, in convenient form, the work that has been accomplished to date.

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[1]Stone, M.B. and R.J. Englar, "Circulation Control - A Bibliography of NSRDC Research and Selected Outside References," NSRDC Report 4108, AD 775-284 (Jan 1974).

The items are arranged chronologically and include short abstracts of the technical notes, formal reports, and technical papers prepared by personnel of the Aviation and Surface Effects Department. The brief abstracts will enable researchers to determine whether the full report is of particular interest to them. Reports added since the original bibliography[1] begin with Item 23.

Two appendices on outside sources of information are included and arranged in chronological order. The first is limited to presentations on the theory of circulation control; many of them represent the early foundations of circulation control theory. The second appendix consists mainly of technical papers and lectures that augment and supplement the in-house and theoretical presentations.

BIBLIOGRAPHY

1. Williams, Robert M., "Some Research on Rotor Circulation Control," Third CAL/AVLABS Symposium on Aerodynamics of Rotary Wing and V/STOL Aircraft, Vol. 2 of Proceedings, Cornell University, Buffalo, New York (18-20 Jun 1969).

Interest in the feasibility of a two-bladed stowed-rotor aircraft with relatively high disk loading led to a review of high lift schemes. The primary considerations for the choice of a rotor system were hover efficiency, size, gust insensitivity during the transition, and rigidity.

As a first step, the attempt was made to select the most efficient two-dimensional high lift airfoil section. This was done by defining an equivalent lift-to-drag ratio which included a penalty for the power required for either suction or blowing. The total power penalty can be expressed in terms of a drag coefficient defined by:

Blowing: C_{d_T} = (wake drag + jet momentum flux + ram drag)/qS

Suction: C_{d_T} = (wake drag + suction quantity x pressure drop)/qS

Results show that the method of circulation control by tangential blowing over the rounded trailing edge of an ellipse is superior in efficiency. Also, this section adequately fulfills the other requirements for a stowable rotor with the additional advantage that it may completely eliminate mechanical cyclic control by modulation of the supply air. Inasmuch as considerable research had already been completed at the National Gas Turbine Establishment, this rotor system was ideally suited for further study.

2. Williams, Robert M. and Harvey J. Howe, "Two-Dimensional Subsonic Wind Tunnel Tests on a 20-Percent Thick, 5-Percent Cambered Circulation Control Airfoil," NSRDC Technical Note AL-176, AD 877-764 (Aug 1970).

An experimental program was undertaken to develop circulation control high lift airfoils for rotary wing vehicle application. The basic

method involves ejecting a thin jet sheet of air tangentially over the rounded trailing edge of a thick airfoil, usually of modified elliptic cross section. The jet sheet remains attached to the rounded trailing edge but eventually separates on the underside. The present report presents results for a 20-percent-thick cambered ellipse. The lift, drag, and section equivalent lift-drag ratio data indicate that this model is one of the most efficient high lift airfoils yet tested.

3. Englar, Robert J., "Two-Dimensional Transonic Wind Tunnel Tests of Three 15-Percent-Thick Circulation Control Airfoils," NSRDC Technical Note AL- AD 882-075 (Dec 1970).

Two-dimensional transonic wind tunnel tests were conducted on three 15-percent circulation control elliptic airfoils over the range $0.3 \leq M_\infty \leq 0.9$. Model configurations included a pure elliptical shape with both jet flap and tangential upper surface trailing edge blowing and an elliptical shape with a rounded trailing edge and tangential blowing. The rounded trailing edge configuration gave the best performance of the three at low speeds but performance deteriorated rapidly above $M_\infty = 0.55$ due to detachment of the Coanda jet. The elongated trailing edge and associated larger effective radius downstream of the slot enabled the tangentially blown pure ellipse to extend the jet detachment Mach number to 0.7; at this velocity, maximum equivalent lift-to-drag ratios of 22 at C_ℓ of 0.44 and $\alpha = -1.2$ degrees were achieved. The jet flap proved to be inferior to the tangentially blown configuration in all respects except its ability as a thrusting, drag-reducing body.

4. Williams, Robert M. and C.L. Bernitt, "Theoretical Performance of a Pure Jet Flap Rotor at High Advance Ratios," NSRDC Technical Note AL-189, AD 726-706 (Dec 1970).

The theoretical performance of a jet flap rotor was examined at advance ratios greater than 1.0. The rotor was four bladed with purely elliptical airfoils of 15-percent thickness ratio. Each airfoil had two plenum chambers which supplied air to slots located beneath the leading and trailing edges. Since the rotor operated in cruise at advance ratios

greater than unity, the retreating blade was immersed in reverse flow. The lift and moments were controlled by ejecting a jet sheet out of the trailing edge on the advancing side of the azimuth and out of both the leading and trailing edge on the retreating side of the azimuth.

Standard blade element theory was used to calculate jet flap rotor performance thrust coefficients representative of actual full-scale rotor operation. It was shown that good performance can be obtained by using the jet flap and that substantially better performance can be achieved by using a circulation control airfoil.

5. Ottensoser, Jonah, "Description and Calibration of a Wall Balance System for a 15- by 20-Inch Subsonic Wind Tunnel," NSRDC Technical Note AL-196 (Feb 1971).

A wall balance for a 15- by 20-inch subsonic wind tunnel was built and calibrated. This system uses a set of three concentric rings on each of the two walls of the tunnel test section to measure lift, drag, and pitching moment. Maximum loads are $\pm$300 pounds in lift and $\pm$50 pounds drag. Calibration results indicate that the balance is reliable to within 1 percent in lift and drag. Moment results are only fair--at best their accuracy is only to within 5 percent.

6. Englar, Robert J. and Robert M. Williams, "Design of a Circulation Control Stern Plane for Submarine Applications," NSRDC Technical Note AL-200, AD 901-198 (Mar 1971).

A nondeflecting circulation control (CC) submarine stern plane was designed in order to provide maneuverability control and eliminate the possibility of catastrophic crash dives due to stern plane jamming. Symmetric elliptic sections with tangential blowing out of upper and lower slots over a rounded trailing edge were selected because of their high lift and equivalent aerodynamic (hydrodynamic) efficiencies. The CC model stern plane so designed was restricted by the requirement to maintain the same planform as a conventional stern plane, by the existence of a large boundary layer on the main body, and by the additional requirement of zero deflection. With moderate blowing, it was able to meet or

exceed the prescribed lifting (maneuvering) requirements for the conventional deflecting control surface. In the event of a blowing failure, the fixed nature of the plane provides inherent stability.

The technical note includes a detailed design procedure, supporting experimental data, and the final geometry of the blown model stern plane. Also included is a similar study on an alternate blown configuration with end plates which demonstrated improved performance over the first design.

7. Englar, Robert J., "Two-Dimensional Subsonic Wind Tunnel Tests of Two 15-Percent-Thick Circulation Control Airfoils," NSRDC Technical Note AL-211, AD 900-210L (Aug 1971).

Two relatively thin circulation control (CC) elliptic airfoils were tested subsonically to determine their characteristics as proposed helicopter rotor tip sections. These airfoils employ tangential trailing edge (Coanda) blowing and previous tests had demonstrated very promising transonic characteristics. It was the purpose of the subsonic retests to determine whether these thin sections could generate equally impressive characteristics at low speeds. Because of its more forward slot location, the 15-percent-thick pure elliptic section displayed effective subsonic operation at positive angle of attack, reducing drag while producing lift coefficients up to 3.5. The rounded trailing edge configuration, with further aft slot and better Coanda deflection of the jet, generated lift coefficients up to 4.25 (with a preference for negative incidence) but experienced higher drag levels. Leading edge separation limited the performance of both sections because of their small nose radii and the low test Reynolds number. At a fixed momentum coefficient, performance improved as slot height was reduced. This was due primarily to higher energy levels in the jet sheet, but the lower bound on slot height was limited by boundary layer buildup in very small nozzles. Circulation control gave both CC sections far greater lift capabilities than the more conventional NACA 0012 blade section but their equivalent efficiency was less at positive incidence due to blowing power requirements.

8. Williams, Robert M. and R.A. Hemmerly, "Determination of the (Ideal Practical) Hover Efficiency of Circulation Control Rotors," NSRDC Technical Note AL-212, AD 902-068L (Aug 1971).

Closed form equations were developed for an approximate analysis of the maximum performance of a circulation control rotor (CCR). They conveniently showed the contribution of the induced, profile, compressor, and coriolis powers in terms of the basic airfoil equivalent lift-to-drag ratios. A range of rotor taper ratios and solidities was examined under the constraint of ideal twist distribution. Comparison with a conventional rotor (using a NACA 0012 reference airfoil) indicated that the CCR can achieve comparable overall hover efficiencies (Figure of Merit) at significantly higher values of rotor thrust-coefficient-to-solidity ratio. The presentation includes a brief discussion of the implications of these characteristics for helicopter design.

9. Williams, Robert M., "Analysis of the Hover Performance of a High Speed Circulation Control Rotor," NSRDC Technical Note AL-221, AD 904-474 (Aug 1971).

The method described for calculating the detailed hover performance of any arbitrary CCR includes such higher order effects as nonuniform inflow, internal ducting losses, and experimental airfoil data. Calculations were performed on an untwisted constant chord blade with varying section thickness and camber. Calculated hover Figures of Merit exceeded 0.80 for this rotor at thrust-coefficient-to-solidity ratios of 0.20. The optimum pitch angle was determined for each thrust coefficient, and the effects of slot height and tip Mach number were also analyzed. A comparison was made with a conventional rotor system of the same solidity.

10. Englar, Robert J., "Two-Dimensional Subsonic Wind Tunnel Tests on a Cambered 30-Percent-Thick Circulation Control Airfoil," NSRDC Technical Note AL-201, AD 913-411L (May 1972).

A relatively thick CC elliptic airfoil section with a thickness-to-chord ratio of 0.30 and a circular arc camber of 1.5 percent at the midchord was tested subsonically to determine its aerodynamic properties

as a midspan blade section on a blown helicopter rotor. The two-dimensional tests established the ability of the section to generate the required lift at low and negative incidence. Lift coefficients up to 6.5 were produced at moderate momentum coefficient ($C_\mu \leq 0.24$). High drag of the unblown bluff ellipse was greater reduced by the application of very moderate blowing, and equivalent efficiencies of 47 (including power required for blowing) were generated at C_ℓ 1.9. Section performance was found to be heavily influenced by upper and lower aft surface flow separations, especially at the larger positive and negative angles of attack. In addition, both low Reynolds number and an increase in slot height were detrimental to section lift capability. Nevertheless, the ability to operate at high lift coefficients essentially independent of angle of attack, and with large lift augmentation from relatively low blowing, promises to provide an effective blade section for heavy lift application.

11. Williams, Robert M. and E.O. Rogers, "Design Considerations of Circulation Control Rotors," Paper 603, 28th National Forum of the American Helicopter Society, Washington, D.C. (18-19 May 1972).

The concept of circulation control by means of tangential blowing about bluff trailing edge airfoils is introduced. The major aerodynamic characteristics which are applicable to rotor design are described. These include such revolutionary features as the generation of lift independent of velocity (in the region of boundary layer control) and the development of efficiencies comparable to present airfoils but at much higher lift coefficients. The application of these new airfoils to a rotor with no mechanical cyclic control is next discussed, and it is shown that a broad range of applications are possible. Significant improvements in rotor thrust capability, hover efficiency, cruise efficiency, and weight efficiency are predicted. Some experimental results are shown. A very high-speed helicopter design and a heavy lift helicopter design are used to illustrate the operational improvements which may be expected with the circulation control concept. It is demonstrated that this rotor may offer a breakthrough in helicopter design and performance resulting in a virtual doubling of productivity.

12. Rogers, Ernest O., "Critical Mach Numbers of Circulation Control Airfoils as Determined by Finite-Difference Methods," NSRDC Technical Note AL-273, AD 909-874L (Aug 1972).

The critical Mach number of several circulation control elliptic airfoils was calculated for various circulation and angle-of-attack conditions. The full inviscid compressible flow equations were solved by finite-difference relaxation methods. The sections examined are candidates for use on helicopter rotor blades. Comparisons with conventional sections indicated that the elliptic circulation control airfoils had a significantly higher critical Mach number.

13. Williams, Robert M., "Recent Developments in Circulation Control Rotor Technology," Meeting of Advisory Group for Aerodynamics R&D (Aerodynamics of Rotary Wings), AGARD-CPP-111, Marseilles, France (13-15 Sep 1972).

The results of recent research on the historical concept of applying circulation control to rotor blades are presented. A high-speed helicopter application was used to illustrate the potential of this rotor for a major breakthrough in the areas of rotor efficiency, parasite drag, and weights, leading to a large improvement in aircraft productivity. Details of the hover, transition, and high-speed cruise performance are presented. Some problems of autorotation, vibrations, and blade dynamics are also discussed.

14. Englar, Robert J. and J. Ottensoser, "Calibration of Some Subsonic Wind Tunnel Inserts for Two-Dimensional Airfoil Experiments," NSRDC Technical Note AL-275, AD 913-412L (Sep 1972).

The installation of parallel wall inserts in the NSRDC 8- x 10-foot subsonic tunnel provided a 3- x 8-foot channel to serve as a high flow quality two-dimensional test section for high lift testing. A detailed flow survey indicated good flow uniformity, negligible angularity, a thin wall boundary layer at the model station, and a pronounced effect of trailing edge wall flaps on controlling test section dynamic pressure. The lift and pressure distributions for a pair of two-dimensional airfoil

sections tested in the facility were in good agreement with reference data but the agreement was less satisfactory for wake rake drag. The strong influence of model lift on test section dynamic pressure measurement was noted, and a measurement technique was developed which was independent of the static pressure field propagating from the airfoil.

15. Hoffman, J.A., et al., "A Study of Stability and Control Characteristics of a Circulation Control Rotor and Helicopter," Mechanics Research, Inc. under NAVAIR Contract N00019-72-C-0402 (23 Feb 1973).

This study of the stability and control characteristics of a circulation control rotor (CCR) and helicopter essentially involved two separate activities: methods development and handling qualities evaluation studies. The methods development efforts concentrated on the modification of the MRI MOSTAB computer program to include mathematical models for the CC airfoils and the influence of certain high-frequency rotor blade aeroelastic modes. Stability and control derivatives generated by MOSTAB-CCR (the modified CCR version of MOSTAB) were then used to perform an exploratory investigation of the handling qualities of a typical CCR helicopter.

Because of its ready availability from the government inventory, its small size, and the absence of "built-in" stability augmentation systems, the Hughes OH-6A Helicopter was selected as a model for use during the CCR stability and control studies.

In the actual study, the methods development preceded the handling qualities evaluations, but documentation of these activities is presented in reverse order. The handling qualities considerations (i.e., the stability and control examinations) are presented first since this component led to the fundamental conclusions of interest. A detailed documentation of all new methods follows the discussion of handling qualities.

16. Englar, Robert J. and R.M. Williams, "Test Techniques for High Lift Two-Dimensional Airfoils with Boundary Layer and Circulation Control for Application to Rotary Wing Aircraft," Canadian Aeronautics and Space Journal, Vol. 19, No. 3, pp. 93-108 (Mar 1973).
Also published as NSRDC Report 4645, AD-A-015-623 (Jul 1975).

Extensive testing experience with very high lift monoelement blown airfoils to be employed by rotary wing aircraft has necessitated the development of unconventional two-dimensional test techniques. The experimental and analytical results presented here should assist future investigators to conduct similar tests accurately.

The primary problem of high lift two-dimensional testing, wall boundary layer separation due to severe adverse pressure gradients on the model, is discussed as are the serious errors introduced by this phenomenon. Closely related is the preference for pressure instrumentation (both lift and drag) over the simpler but considerably less accurate force balance. The detailed discussion concerns the additional considerations which must be given to blown airfoil testing, e.g., blowing coefficients, necessary modification to pitot-traverse drag calculations, and definition of an equivalent lift-drag ratio which takes into account the penalty for blowing. Such additional test problems as wall and blockage corrections, Reynolds number effects, leading edge separation, and flow visualization are also addressed.

17. Wilkerson, Joseph B., "Design and Performance Analysis of a Prototype Circulation Control Helicopter Rotor," NSRDC Technical Note AL-290, AD 912-213L (Mar 1973).

A circulation control rotor (CCR) was designed for application to existing, conventional-speed helicopters of the 5000- to 10,000-pound weight class. The design methodology tended to minimize rotor-induced power in hover while the rotor operates at near maximum airfoil section efficiency. The particular design was constrained by conventional disk loadings and blade tip speeds to be consistent with available helicopter engine/transmission combinations. The design is near optimum within these constraints and current available data. Circulation control airfoil and slot

geometry design considerations are shown. Tip speed, solidity, and disk loading were varied to show performance sensitivity to those parameters and to define the conditions of best overall rotor aerodynamic efficiency. The constrained CCR design was found to operate best at a thrust coefficient/solidity ratio around 0.12. At this condition, the hover Figure of Merit improved with increased disk loading while cruise aerodynamic efficiency was relatively insensitive to changes in disk loading. Overall performance exceeded or equalled that of conventional rotor systems for the same weight class vehicle.

18. Stone, Michael B., "Higher Harmonic Circulation Control Rotor Model, Model Instrumentation and Data Acquisition," NSRDC Technical Note AL-288 (Apr 1973).

A higher harmonic CCR was tested in the 8- x 10-foot subsonic wind tunnel at various advance ratios, blade tip Mach numbers, blowing air pressures, shaft angles, and collective angles. The model was instrumented with strain gages, pressure transducers, thermocouples, magnetic pickups, and a pitch-roll trim resolver. This information was recorded on an analog to digital data acquisition system and on FM tape recorders for later digitization.

The purpose was to provide descriptive documentation of the model instrumentation and data acquisition portion of the test, and no attempt was made to elaborate on helicopter or higher harmonic theory.

19. Reader, Kenneth R., "Evaluation of a Pneumatic Valving System for Application to a Circulation Control Rotor," NSRDC Report 4070 (May 1973).

A cam-type penumatic valving system was developed to provide helicopter rotor control/trim forces. This valving system provides both first and second harmonic rotor control by means of modulating both blade pressures and mass flow rates. Data are presented for (1) constant one-per-rev and two-per-rev air modulation, (2) constant and tapered slot distributions (3) two pipe volumes, and (4) three cam-nozzle gap distances.

The present study demonstrated that air pressure and mass flow rate can be modulated by means of a simple cam valve system. As the gap between the periphery of the cams and the nozzle was increased for a given

cam geometry, the mean pressure and mass flow rate increased and the peak-to-peak pressure and mass flow rate decreased. It was also demonstrated that a smooth transfer of the total pressure and mass flow rate occurred in going from a one- to a two-per-rev component (or vice versa).

20. Wilkerson, Joseph B. et al., "The Application of Circulation Control Aerodynamics to a Helicopter Rotor Model," Paper 28, 29th Annual Forum of American Helicopter Society, Washington, D.C. (10-11 May 1973).

On the basis of several years of two-dimenisonal research in the field of circulation control airfoils, a higher harmonic CCR model was designed, built, and tested at NSRDC. Unique features of the model included blades with elliptical-shaped circulation control airfoils and a simple cyclic control mechanism based on the variation of blade pressure rather than blade pitch. The model demonstrated that trimmed flight could be achieved without moving parts other than the rotating blades and, further, that the high lift capability and efficiency of circulation control airfoils could be extended into the three-dimensional regime.

Aerodynamic trends displayed by the model were coupled with two-dimensional results to improve the theoretical programs used to predict model performance. Variables such as slot height-to-chord ratios, slot height-to-trailing edge radius ratio, Reynolds number, and Mach number have been identified as factors which significantly affect the performance of circulation control airfoils. These effects have therefore been incorporated into the programs. Good agreement between theory and model results have led to a second generation rotor design.

21. Rogers, E.O., "Numerical Solution of Subcritical Flow Past Airfoils," NSRDC Report 4112 (May 1973). (University of Maryland M.S. Thesis, Department of Aerospace Engineering 1973)

A finite-difference solution technique was developed for subsonic two-dimensional inviscid flow past lifting airfoils. This work is an adaptation of the method used by Sells (1967). The full governing equations of compressible flow are written in terms of a translated velocity potential which is continuous throughout the flow field. This simplifies solutions for bluff airfoils (no Kutta condition) where both angle of

attack and lift coefficient are specified. The computational plane is the interior of a unit circle obtained by mapping the flow field into the interior of the circle. A line over-relaxation matrix method is used for solution of the partial differential equation which in the iteration scheme is coupled with an algebraic equation. The numerical procedure is accurate and well behaved for all subsonic flow conditions.

22. Englar, Robert J., "Subsonic Wind Tunnel Investigation of the High Lift Capability of a Circulation Control Wing on a 1/5-Scale T-2C Aircraft Model," NSRDC Technical Note AL-299, AD 781-856 (May 1973).

A circulation control wing, formed by the deflection of a 15-percent chord flap through 180 degrees to produce a circular cylinder trailing edge with tangential upper surface blowing, was applied to a 1/5-scale model T-2C. The flap span/wing semispan ratio was 0.495, consistent with the flapped span of the conventional aircraft. Subsonic tests were conducted in the NSRDC 8- x 10-foot wind tunnel over a dynamic pressure range from 5 to 40 psf (Reynolds number based on mean aerodynamic chord of 0.59 to 1.68 million). Flap deflection was varied from 0 to 180 degrees, thus comparing the configurations of blown flap (moderate to high lift, lower drag for takeoff) and the Coanda trailing edge (high lift and high drag for landing). At a dynamic pressure of 30 psf (Reynolds number of 1.43 million), a maximum lift coefficient of 3.33 was generated by a momentum coefficient of 0.156, compared to $C_{L_{max}} = 1.70$ for the conventional aircraft with a 37-percent chord slotted flap deflected 33 degrees.

23. Englar, Robert J., "Experimental Investigation of the High Velocity Coanda Wall Jet Applied to Bluff Trailing Edge Circulation Control Airfoils," NSRDC Technical Note AL-308, AD 771-690 (Jun 1973). Also published as M.S. Thesis, University of Maryland, Department of Aerospace Engineering (Jun 1973), and as NSRDC Report 4708, Aero Report 1213, AD-A-019-417 (Sep 1975).

A two-dimensional experimental investigation, intended to probe the mechanism for loss of performance of circulation control elliptic airfoils in compressible flow, was conducted subsonically on a 20-percent thick modified elliptic profile employing high Coanda wall jet velocities.

The results include detailed pressure distributions (both normal and chordwise) and trailing edge shear stress measurements made with a hot film anemometer for a range of jet slot heights and jet total pressures corresponding to high subsonic, sonic, and supersonic jet velocities. Jet Mach numbers of almost 1.3 were found to have no adverse effects on the airfoil performance, and the degrading jet detachment phenomenon was never encountered. Significant differences in the jet flow field with and without an external freestream were noted, as was the deviation of the static pressure across the jet from a constant value as assumed in conventional boundary layer analysis. Airfoil lift performance was found to vary with slot height, while location of the jet separation point was provided by the detailed shear stress measurement. Also discussed is the calibration and use of the hot film shear stress probe.

24. Englar, Robert J., "Investigation Into and Application of the High Velocity Circulation Control Wall Jet for High Lift and Drag Generation on STOL Aircraft," AIAA Paper No. 74-502 presented at the AIAA 7th Fluid and Plasma Dynamics Conference, Palo Alto, California (17-19 June 1974). Also published as DTNSRDC Report 76-0142, AD-A-034-619 (Nov 1976).

The concept of circulation control by tangential upper surface blowing over a circular trailing edge has been investigated for application to fixed wing STOL aircraft. Experimental investigations on both two- and three-dimensional airfoils employing nominal blowing have demonstrated lift gains almost triple that of the conventional flapped airfoil and associated large increases in drag (which, in addition to the high lift, further reduces landing velocities and distances). An additional two-dimensional investigation into the basic fluid mechanics of the concept has shown that jet Mach numbers considerable above choked produced no adverse effects on the mechanism of the trailing edge Coanda flow, but instead yielded additional lift gains. These results appear quite promising where high lift generation is desired for a STOL

aircraft having a nominal amount of auxiliary bleed air available, but where substitution of increased pressure ratios can produce added jet velocity to obtain the required momentum (blowing) coefficient.

25. Ottensoser, Jonah, "Two-Dimensional Subsonic Evaluation of a 15-Percent Thick Circulation Control Airfoil with Slots at Leading and Trailing Edges," NSRDC Report 4456, Aero Report 1197 (Jul 1974).

A 15-percent-thick circulation control elliptical airfoil section with slots at both leading and trailing edges for tangential blowing was evaluated in a subsonic wind tunnel to determine its potential for high-speed (300-400 knot) helicopter rotor systems. Fore-and-aft slot utilization was determined by local flow direction over the blade as it revolved around the azimuth. Aerodynamic performance was not affected by the addition of an unblown leading edge slot except beyond the usable positive angle of attack range where some loss in lift and increase in drag were noted. At equal plenum pressures, simultaneous blowing from the leading and trailing edges resulted in a decrease in lift, an increase in drag, and a more positive pitching moment than for trailing edge blowing alone. However, for its intended application to the retreating blade area of the rotor disk, the dual slotted airfoil can provide positive lift for both fore and aft flow directions--a condition which is not readily achievable with the conventional rotor airfoil.

26. Englar, Robert J., "Subsonic Two-Dimensional Wind Tunnel Investigations of the High Lift Capability of Circulation Control Wing Sections," DTNSRDC Report ASED-274 (Apr 1975).

Two series of circulation control wing airfoil sections, formed by the conversion of the sharp trailing edge into a circular bluff surface with tangential upper surface blowing, were evaluated subsonicaliy to determine their high lift characteristics as potential STOL wing sections. Parameters investigated which had noticeable effect on the blown airfoil performance include leading edge devices (type of device and degree of deflection), trailing edge configuration (radius, slot location, deflection, etc.), Reynolds number, airfoil incidence, momentum coefficient,

slot height, and nozzle pressure ratio. Maximum lift coefficients, roughly triple those of the flapped conventional sections, were generated at incidence slightly less than the conventional stall angles and at blowing rates obtainable from bleed of state-of-the-art turbojet engines. An experimental investigation into the lift augmenting effects of pulsed unsteady blowing was conducted on a smaller radius trailing edge configuration. An additional investigation was conducted to determine the effects of spoilers or similar disturbances ahead of the jet exit. The results of the above investigations provide a data base for the prediction of the aerodynamic characteristics of aircraft employing circulation control trailing edges to increase their STOL capability.

27. Montana, Peter S., "Experimental Investigation of Three Rotor Hub Fairing Shapes," NSRDC Report ASED-333 (May 1975).

A series of subsonic wind-tunnel evaluations was undertaken to establish minimum drag fairings for helicopter hubs as part of the Helicopter Drag Technology Program. The data reported herein were taken to investigate the flow phenomena affecting helicopter rotor hubs. Three large, 25-percent thick, analytically faired hubs were evaluated (both with and without simulated rotor blade shanks) over a wide range of angles of attack at full scale Reynolds numbers. Forces, moments, and pressures were measured on the hubs. In addition, fluorescent oil flow visualization was used to aid in the qualitative understanding of the flow. Of the three fairing shapes evaluated, the reflex curvature fairing was shown to have significantly lower drag at small angles of attack than the other shapes.

28. Englar Robert J., "Circulation Control for High Lift and Drag Generation on STOL Aircraft," AIAA Journal of Aircraft, Vol. 12, No. 5, pp. 457-463 (May 1975).

The concept of circulation control by tangential upper surface blowing over a circular trailing edge has been investigated for application to fixed wing STOL aircraft. Experimental investigations on both two- and three-dimensional airfoils employing nominal blowing have

demonstrated lift gains double to triple that of the conventional flapped airfoil, and associated large increases in drag (further reducing landing velocities and distances). An additional two-dimensional investigation into the basic fluid mechanics of the concept has shown that jet Mach numbers considerably above choked produced no adverse effects on the mechanism of the trailing edge Coanda flow, but instead yielded additional lift gains. These results appear quite promising where high lift generation is desired for a STOL aircraft having a nominal amount of auxiliary bleed air available, but where substitution of increased pressure ratios can produce added jet velocity to obtain the required momentum (blowing) coefficient.

29. Wilkerson, Joseph B. and Drew W. Linck, "A Model Rotor Performance Validation for the CCR Technology Demonstrator," Preprint 902, 31st Annual National Forum of the American Helicopter Society, Washington, D.C. (May 1975); also published in Journal of the American Helicopter Society, Vol. 21, No. 4 (Oct 1976).

Circulation control technology has been further developed at the Naval Ship Research and Development Center by wind tunnel and hover stand evaluations of a second rotor model--the Circulation Control Rotor (CCR). This two-bladed model was preceded by the four-bladed Higher Harmonic Circulation Control (HHCC) rotor. The first model proved that circulation control could be used for cyclic lift control at forward speeds without the use of cyclic pitch. An improved CCR design was accomplished with a theoretical prediction program which was revised by using the results obtained for the HHCC rotor. The performance of both rotor models is compared and an explanation given of how the trends of the CCR data were used to refine the prediction programs. The results of the extensive correlation effort are shown for forward flight and hover. Knowledge gained from the two CC rotors has been applied to the aerodynamic design of the full-scale technology demonstrator, the Kaman XH2/CCR.

30. Abramson, Jane, "Two-Dimensional Subsonic Wind Tunnel Evaluation of a 20-Percent-Thick Circulation Control Airfoil," DTNSRDC Report ASED-311 (Jun 1975).

A circulation control uncambered elliptic airfoil section with a thickness-to-chord ratio of 0.20 was tested subsonically to determine its aerodynamic characteristics. Lift coefficients up to 5 were produced at momentum coefficients of 0.24. The initially high unblown drag coefficients, characteristic of bluff trailing edge airfoils, were greatly reduced at low values of momentum coefficient. It was therefore possible to produce equivalent lift-to-drag ratios in excess of 30 when $C_{\ell} = 1.0$. The ability to produce high lift coefficients essentially independent of angle of attack is indicated by the results of this investigation.

31. Hemmerly, Rodney A., "Subsonic Wind Tunnel Investigation of a Semi-Span Jet Flapped Wing Designed Primarily for High Speed Flight," DTNSRDC Report ASED-351, AD-A-024-798 (Jul 1975).

The low speed aerodynamic characteristics of an 18-percent scale, semi-span jet flapped wing designed primarily for transonic maneuverability were investigated in the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) 8- x 10-Foot Subsonic Wind Tunnel. These low speed characteristics were obtained to aid in determining if adequate STOL performance could be obtained by a high speed jet flapped wing, thus eliminating the need for additional high lift devices required solely for the landing and takeoff modes of operation. The structure of this investigation provided a data basis for a jet flapped wing with and without a glove. During the investigation the maximum lift coefficient obtained was 1.96 corresponding to a blowing coefficient and angle of attack of 0.326 and 13.6 degrees respectively. This is approximately a 280 percent improvement in lift over the wing at the same incidence with no blowing. Evaluation of the roll power at the low speed condition indicates that adequate power is available to control an aircraft equipped with a gloved jet flapped wing in the takeoff and landing modes. In general, subsonic performance of the gloved wing was limited in this investigation by large vorticity generation and detached flow.

32. Williams, Robert M., "Application of Circulation Control Rotor Technology to a Stopped Rotor Aircraft Design," presented at the First European Rotorcraft and Powered Lift Aircraft Forum, Southampton, England (22-24 September 1975). Also published as DTNSRDC Report 4574 AD-A-029-168 (Dec 1975).

This paper presents the application of circulation control rotor (CCR) technology to a revolutionary new aircraft concept -- the X-Wing stopped rotor V/STOL. This design affords the potential for major advances in rotary wing aircraft speed, range-payload, productivity, and cost through the application of highly innovative aerodynamic and structural design. The technology base for the concept has been derived from almost 6 years of related CCR aerodynamic and structural design studies at the David W. Taylor Naval Ship Researh and Development Center (DTNSRDC) and from earlier research in the United Kingdom. Additional design insight has been gained from the experience of various stopped and stowed rotor concepts of the 1960's and also from more recent studies of the NASA "oblique wing" transonic transport concept.

33. Reader, Kenneth R. and Joseph B. Wilkerson, "Circulation Control Applied To A High Speed Helicopter Rotor," Preprint No. 1003, 32nd Annual National V/STOL Forum of the American Helicopter Society, Washington, D.C. (May 1976).

An advanced circulation control rotor concept identified as the Reverse Blowing - Circulation Control Rotor (RB-CCR) is discussed from the standpoint of general requirements for high speed flight. This discussion centers on a rotor solidity ratio compromise between hover, transition and cruise requirements. It is shown that the critical solidity requirement occurs in transition where high lift capability is needed while maintaining rotor moment trim. An analytical and experimental investigation of the aerodynamic environment in the transition flight regime (advance ratios of 0.5 to 1.4) indicates that large local yawed flow angles do not severely affect the lift augmentation and maximum lift coefficient of circulation control airfoils.

A RB-CCR model was designed and tested at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). This rotor is unique in its employment of a special circulation control airfoil which has a slot in the leading and trailing edge. The results of several test programs verified the capability of the rotor to perform efficiently in hover and at advance ratios up to 4.0. The model data also demonstrated that the rotor is capable of developing sufficient lift to fly through the critical advance ratio of 0.7.

34. Reader, Kenneth R., "A Control System for the Wind Tunnel Model of A Reverse-Blowing Circulation Control Rotor, (RB-CCR)," DTNSRDC Report 76-0062, AD-A-026-548 (May 1976).

A pneumatic valving system has been developed to provide cyclic and collective control inputs for a circulation control type rotor over an advance ratio range of 0 to 2.0. The design method and experimental techniques utilized in developing the control system for a wind tunnel model of the reverse-blowing circulation control rotor (RB-CCR) are discussed and a tradeoff is presented between two control systems which have potential for the necessary requirements. A cam-collector nozzle system is considered a better choice for the model rotor configuration than a cam-collector ring control system. It was concluded that a system to control the RB-CCR wind tunnel model can be designed by employing the proper area relationships and adhering to a simple design procedure.

35. Williams, R.M., R.T. Leitner, and E.O. Rogers, "X-Wing: A New Concept In Rotary Wing VTOL," presented at the American Helicopter Society Symposium on Rotor Technology, Philadelphia, Pa. (Aug 1976).

The current status of the theoretical and experimental analysis of an advanced Circulation Control (CC), stopped rotor concept called X-Wing is presented. Modifications to classical fixed wing theory to properly represent circulation control aerodynamics and the interference effects of fore and aft swept wings for the stopped rotor mode are discussed. The results generated from this modified theory are

compared with experimental results obtained on a model rotor. Theoretical drag estimation of a full-scale vehicle indicates that the total vehicle parasite drag compares favorably with current fixed wing aircraft. Design tradeoffs for the full-scale aircraft show that for missions requiring less than 30 minutes of hover, a vehicle designed without collective pitch is possible. An elastic slot design is also considered and is shown to enhance both transition and fixed wing performance. The analysis of transition performance is discussed with recommendations of areas needing further study. The results of both the theoretical and experimental analysis of all flight modes show that no fundamentally limiting problems exist at this stage of development.

36. Reader, Kenneth R., "The Effects of Cam and Nozzle Configuration On the Performance Of A Circulation Control Rotor Pneumatic Valving System," DTNSRDC Report 76-0103 (Sep 1976).

Basic research was conducted on the sensitivity of such component parts of a cam-type pneumatic valving system as cam eccentricity, nozzle aspect ratio, nozzle shape, nozzle endplates, slot exit area, and transition zone between the nozzle and blade entrance. Data are presented which show how systematic variations of these components affect the total pressure loss coefficient, the mass flow rate, and the jet velocity. Information on the sensitivity of these parameters enhances the capabilities to design a cam-type pneumatic valve.

It was concluded that cam eccentricity had no effect on the characteristic curve for total pressure loss coefficient versus area coefficient. Accordingly, no stringent requirement should be encountered in changing the cross-sectional shape or the size of the nozzle. Streamlining of the transition section between the nozzle and blade entrance did not affect: the pressure recovery in the operational range of the valve, the shape, the harmonic content of the lost coefficient, or the mass flow rate curves. The addition of endplates to the nozzle reduced the total pressure losses between the hub and the blade.

The area coefficient and total pressure loss coefficient are shown to be adequate parameters to correlate the data for different valve models.

37. Wilkerson, Joseph B., "Aeroelastic Characteristics of a Circulation Control Wing," DTNSRDC Report 76-0115 (Sep 1976).

Static aeroelasticity is examined for a wing with circulation control (CC) airfoils. The airfoils use tangential blowing over a rounded trailing edge to provide a lift augmentation proportional to the jet momentum of the blown air. Airfoil lift and pitching moment magnitudes are dependent on both angle of attack and jet momentum. In combination with an elastic structure, this double dependence of lift and moment can lead to a CC reversal condition, which is analogous to aileron reversal. Increases in jet momentum beyond the reversal point result in lift decreases. Boundaries for torsional divergence and CC reversal are theoretically examined for the simple two-dimensional case and then for a three-dimensional wing. The wing analysis uses a modified lifting line theory and two-dimensional CC airfoil data to evaluate the behavior of a circulation control wing (CCW). Two parameters, lift effectiveness and control effectiveness, define the behavior of an elastic CCW relative to that of a rigid CCW. A modified version of the wing analysis is used for comparison to wind tunnel data from a CCW model. The model had a root attachment device which allowed rigid body wing torsional deflections in response to the aerodynamic pitching moments.

Stall flutter conditions were encountered which involved only the wing bending mode oscillating at the first cantilevered natural frequency. A first order explanation of the flutter is provided by two-dimensional considerations. It is shown that the wing stall flutter boundaries may be established from the two-dimensional analysis by proper scaling and by establishing an aerodynamic equivalence.

The theory was in good agreement with wind tunnel evaluations on a model CC wing. Because of the large geometric twist in the available

model, portions of the wing were at or near angle-of-attack stall conditions even though blowing maintained significant levels of lift coefficient. Such conditions are unique to CC airfoils. This caused some difficulty in obtaining a solution with the lifting line theory which would provide a numerically stable and convergent iteration. The approach used in conjunction with the modified lifting line theory and two-dimensional airfoil data is believed to be the first such analysis, notwithstanding the establishment of divergence and reversal boundaries.

38. Wilkerson, Joseph B., "An Assessment of Circulation Control Airfoil Development," DTNSRDC Report 77-0084 (Aug 1977).

A circulation control CC airfoil development program is presented, including an airfoil designation system. Specific performance objectives are set forth as development goals. Background information includes an assessment of state-of-the-art design practices, a comparison of operational requirements with those of conventional airfoils, and a discussion of previous airfoil performance. Selection and design criteria are described for five new CC airfoils. These designs were wind-tunnel evaluated as two-dimensional models. A limited amount of airfoil data is shown for comparison to the prior data base.

Two of the airfoils were designed with the objective of maintaining high lift augmentation and improving the critical Mach number characteristics, a combination of qualities that was previously nonexistent. Both designs theoretically accomplished the prescribed goals and were validated by experimental results. The development program has advanced the state of the art and nearly doubled the available data base for CC airfoils.

39. Wilkerson, Joseph B., "Static Stability Derivatives of a Model Circulation Control Rotor," DTNSRDC Report ASED-369 (Mar 1977).

Helicopter stability and control characteristics depend to a large extent on the rotor static stability derivatives. The Circulation Control Rotor (CCR) employs trailing edge blowing on the rotor blades to provide both cyclic and collective control functions. Rotor system forces

are therefore functions of two dependent quantities: blowing and angle of attack. This dual dependency suggests that static stability derivatives of a CCR may be somewhat different from those of a conventional alpha dependent rotor system.

Static stability derivatives of a CCR were obtained from a wind tunnel evaluation of a model rotor. The derivatives show general characteristics similar to a conventional rotor in the advance ratio range $0.20 \leq \mu \leq 0.30$. The conventional characteristic of a destabilizing static speed stability term for hingeless rotors appears to be magnified for low advance ratios in the CCR system. At higher advance ratios the static speed stability term becomes neutral and then strongly stable for the CCR. Some other derivatives show the same tendency toward neutral stability as the speed is increased beyond a 0.30 advance ratio. If this trait is corroborated by future full-scale CCR wind tunnel evaluation, it will represent a significant advantage in stability characteristics over current hingeless rotors.

40. Englar, R.J., L.A. Trobaugh and R.A. Hemmerly, "Development of the Circulation Control Wing to Provide STOL Potential for High Performance Aircraft," AIAA Paper No. 77-578 presented at the AIAA/NASA Ames V/STOL Conference, Palo Alto, California (6-8 June 1977).

Research and development are being conducted at the David W. Taylor Naval Ship Research and Development Center to investigate the STOL capability of the Circulation Control Wing (CCW) concept on high performance aircraft. This high lift system, which employs tangential blowing over a rounded trailing edge and requires mass flows characteristic of state-of-the-art turbine engine bleed, has demonstrated the ability to more than double the lift capability of conventional Navy and Marine aircraft. The resulting reduced takeoff and landing speeds and distances plus increased overload capability are achieved without severe compromise of wing structure, weight, or engine arrangement, and without large quantities of ducted hot gas. Based on these anticipated benefits and the results of existing experimental investigations, a program has been initiated to demonstrate

the STOL capability of the CCW concept applied to a full scale A-6 flight demonstrator aircraft. The present paper will address the experimental development and optimization of the CCW system on an A-6 model and will present predicted full scale STOL performance gains for the flight demonstrator.

41. Hemmerly, Rodney A., "An Investigation of the Performance of a J-52-P8A Engine Operating Under the Influence of High Bleed Flow Extraction Rates," DTNSRDC ASED-387 (Aug 1977).

The uninstalled performance characteristics of a J-52-P8A engine operating under the influence of bleed flow extraction rates in excess of the standard specification limits were experimentally evaluated. This investigation was undertaken as part of the Circulation Control Wing Flight Demonstrator Program to assess the engine's capability of supplying airflow to power the STOL aerodynamic system incorporated on the flight demonstrator, and to define a data base from which higher confidence level analytical STOL performance evaluations could be obtained. Results of the investigation indicate that bleed flow extraction rates significantly greater than the standard specification limits are obtainable. An endurance evaluation of the engine operating under the influence of the high bleed flow extraction rates indicates that these extraction rates do not adversely affect the J-52-P8A engine. The results of the endurance evaluation should qualify the J-52-P8A engine for the proposed Flight Test Program.

APPENDIX A

SOURCES OF INFORMATION ON THE THEORY OF CIRCULATION CONTROL BY TANGENTIAL BLOWING ABOUT A ROUNDED TRAILING EDGE

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APPENDIX B

OUTSIDE PUBLICATIONS AND LECTURES ON CIRCULATION CONTROL

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